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Ozone Effects on Agricultural Crops: Statistical Methodologies and Estimated Dose-Response Relationships

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16. ABSTRACT

The National Crop Loss Assessment Network (NCLAN) began in 1980 to coordinate research on the investigation of the impact of ozone on agricultural crops. A major objective was to develop dose-response relationships between yield of major agricultural crop species and ozone pollution in order to estimate the economic effects of ozone. This paper reports on the statistical methodologies used in combining the dose-response information for each species over sites and years, and serves as a summary of the ozone dose-respose relationships obtained from the NCLAN studies. All dose-response relationships between yield and ozone were characterized with the polynomial response function and the nonlinear Weibull response function. This paper presents the general methodology for both models and the dose response equations for the Weibull model.

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Ozone Effects on Agricultural Crops: Statistical Methodologies and Estimated Dose-Response Relationships

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ABSTRACT

The National Crop Loss Assessment Network (NCLAN) began in 1980 to coordinate research on the impact of ozone (O_3) on agricultural crops. During a 7-yr period, the program investigated 14 crops at sites across the country in a total of 41 studies. A major objective was to develop dose-response relationships between yield of major agricultural crop species and ozone pollution in order to estimate the economic impact of ozone pollution. This paper outlines the statistical methodologies used in combining the dose-response information for each species over all NCLAN studies, and summarizes the ozone dose-response relationships obtained. Differences in experimental designs, treatment combinations, and levels of ozone across studies invalidated the conventional analysis of variance approach to combining information across studies. Regression analyses, with weighted least squares and transformations as needed, were used. Dose-response relationships between yield and ozone were quantified with the nonlinear Weibull response equation and with confidence interval estimates of percentage yield losses. Significant yield losses from ozone were found for 13 of 14 crops studied. The nature of the yield response to ozone differed among crops with soybean [*Glycine max* (L.) Merr.] being the most sensitive and showing a nearly linear response. Losses from ozone at 0.06 $\mu L\ L^{-1}$ compared with 0.025 $\mu L\ L^{-1}$ were estimated as high as 20%. The impact of ozone was shown to be affected by level of moisture stress but not by SO_2.

IN ORDER TO COORDINATE RESEARCH on the effects of air pollution on major agricultural crops, the Environmental Protection Agency funded the National Crop Loss Assessment Network (NCLAN), which began in 1980. The primary objective of the NCLAN program was to investigate the impact of O_3 on yield of major agricultural crops. The NCLAN field experiments were conducted from 1980 to 1986 at four to seven sites across the USA. Open-top chambers (Heagle et al., 1973) were used to control levels of gaseous pollutants in the plant canopy, and similar experimental protocol was followed at all sites (Heagle et al., 1979, 1988; Heck et al., 1984a,b). The primary pollutant investigated was O_3, although interactions with other factors such as SO_2, cultivars, and moisture stress also were studied. The program studied the response to O_3 for 13 single species and two grass-legume mixtures. Eight species were represented by more than one cultivar and nine species were studied in more than one environment (site and/or year).

All experimental designs used several dose levels of O_3 in order to formulate dose-response relationships for yield (Heagle et al., 1986a; Heck et al., 1984a,b; Kohut and Lawrence, 1983; Kress and Miller, 1983). Polynomial response models, which are linear in the parameters, and nonlinear Weibull models (Rawlings and Cure, 1985), which are nonlinear in the parameters, were used to quantify the dose-response relationships. For the final NCLAN economic assessment, a dose-response equation incorporating all NCLAN data for each species was developed. The objectives of this paper are to outline the statistical methodologies employed in analyzing these data, and to summarize dose-response equations for the effect of O_3 on crop yield.

MATERIALS AND METHODS

The methodologies of the NCLAN studies have been previously described (Heagle et al., 1986a,b, 1988; Heck et al., 1984a,b; Kohut and Laurence, 1983; Kress and Miller, 1983; Temple et al., 1985). Forty-one field experiments involving 14 crops were conducted by the NCLAN program during the field seasons of 1980 to 1986. The reader is referred to Heagle et al. (1988) for a summary description of these studies (giving crop species, cultivars, treatment factors, and amount of replication) and references for further details on each. Emphasis of the studies was on four major agricultural crops (corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; soybean; and wheat *Triticum aestivum* L.) and three forages

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(alfalfa, *Medicago sativa* L., and two grass-legume mixtures). The effect of O_3 was investigated in all studies. Several experiments included the additional treatment factors of SO_2 (12 studies) or moisture stress (15 studies). Alfalfa and one grass-legume mixture were studied during a 2-yr growth period.

While the basic NCLAN protocol was similar for all studies, the experimental designs varied; completely random designs, randomized complete-block designs, split-plot designs, and single replicates of 2-factor factorials were used. The experimental designs and cultivars used, and the levels of O_3 and SO_2, and moisture chosen were determined by the specific objectives and resources of each study. Ozone treatment levels were defined in terms of O_3 levels in ambient air, levels remaining after charcoal filtering ambient air, and levels attained after addition of either constant or proportional amounts of O_3 to ambient air during a specified time period (7 or 12 h) of each day. Failure to precisely meet the target levels and natural variation in ambient levels caused slight differences in realized seasonal average O_3 levels across replicates. This introduced some imbalance within each data set, which caused the conventional analysis of variance for each experiment to be only approximately correct. In addition, differences in experimental designs, treatment factors, and levels of the treatment factors over experiments invalidated the conventional analyses of variance methods for combining data. Therefore, all combined analyses used regression models in which the levels of O_3 and SO_2 were treated as continuous variables. For all dose-response models, the dependent variable was yield (kg ha^{-1}), and the independent variables were seasonal arithmetic O_3 and SO_2 means ($\mu L\ L^{-1}$). All models included fixed effects to account for site, year, replicate, cultivar, and moisture-stress effects, and for the effects of frustum tops on some chambers in the Raleigh, 1982 cotton study (Heagle et al., 1986a). Other information, such as initial growth measurements and companion-plot data, were used as potential covariates.

Residuals Analysis

The first stage of the coordinated analysis used the combined data for each crop species to investigate behavior of residuals for evidence of violations of the least squares assumptions. For the residuals analysis, plot size and shape were standardized to the extent possible by subsetting the data using 1-m row segments of the plots on which the basic data were recorded in most studies. For example, a study that used two cultivars as subplot treatments within each chamber would have a basic plot size of one 2-m row. A second study that used one cultivar would have a basic plot size of two 2-m rows. The data in the latter would be restructured to give two data sets each having plot sizes of one 2-m row in agreement with the former. Pooled residuals from the appropriate analyses of variance for the replicated studies and from overfit polynomial models for the single-replicate factorial experiments were used in the residuals analyses.

Residuals (residual vs. predicted values) and normal plots of the pooled residuals from all studies within crops were used to check for nonnormality, outliers, and heterogeneous variances, and Bartlett's chi-squared test of homogeneity of variances (Box et al., 1978) was used to compare error variances within and among studies by species. If Bartlett's test showed significant heterogeneity of variance, the residuals from weighted least squares analyses were inspected to determine if weighting alone was sufficient to account for the observed heteroscedasticity. (The observations in each data set were weighted by the inverse of the error variance estimated for that data set, or by the inverse of the pooled error variance when tests of homogeneity permitted pooling.) In addition, the Box-Cox procedure (Box and Cox, 1964) was used to seek power transformations that would reduce heterogeneity of variances and improve normality. The minimum pooled experimental error sum of squares over all studies for the species was used as the criterion for determining the optimal transformation for the species.

Dose-Response Equations

All O_3 dose-response relationships were characterized both with polynomial models of the appropriate degree and with the Weibull response model (Rawlings and Cure, 1984). Only the results for the Weibull response model are reported here. A complete summary of analyses for both polynomial and Weibull models and a comparison of the two models are to be presented in a North Carolina Agricultural Research Bulletin.

The Weibull dose-response model expresses the mean response to O_3 as:

$$\xi(Y_i) = \alpha^* \exp\left[-\left(\frac{O_3}{\omega}\right)^{\lambda}\right] \qquad [1]$$

where α^* is the theoretical yield at zero ozone, ω is a scale parameter on O_3 dose and reflects the dose at which expected response is reduced to $0.37\alpha^*$, and λ is a shape parameter affecting the change in the rate of loss in expected response. (The above notation uses ω and λ as parameters in place of σ and c, respectively, as used in Rawlings and Cure, 1985). This models the effect of O_3 as a multiplicative effect on the yield α^*. If $\lambda = 1$, the exponential decay curve is obtained with constant *relative* rate of loss $-(1/\omega)$ for all values of O_3. For $\lambda > 1$, the relative rate of loss increases at a rate proportional to $O_3^{(\lambda-1)}$. The effects of other factors in the studies (blocks, cultivars, SO_2, and covariates) are included as $\alpha(x_i)$ terms in α^*, $\alpha^* = [\alpha + \alpha(x_1) + \cdots + \alpha(x_k)]$. This model presumes that the proportional decline due to O_3 is not affected by the level of the other factors, i.e., there is no interaction between O_3 and the other factors on the multiplicative scale.

The response variable was transformed and/or weighted least squares was employed as indicated by the residuals analyses. When a transformation was used, the Weibull response model was similarly transformed to retain the original definition of the parameters. Block and linear effects of the treatment factors (moisture and SO_2) were retained in the α^*-term even when nonsignificant in order to provide estimates of the effects.

Relative yield losses (RYL) due to O_3 were estimated from the fitted Weibull response equations as:

$$\mathrm{RYL} = 1 - \frac{\hat{Y}_0}{\hat{Y}_e} \qquad [2]$$

where $\hat{Y}_e$ and $\hat{Y}_0$ are the estimated mean yields at the reference level of O_3 (0.025 $\mu L\ L^{-1}$, the presumed level of O_3 in clean air) and at some alternative level of O_3, respectively. Confidence interval estimates of RYL were computed assuming normality of the estimates and using the first-order approximation of the variance of a ratio and the first-order approximations of the variances of the parameter estimates obtained from the nonlinear regression. These estimates are referred to as the Wald estimates (Gallant, 1987).

Three categories of dose-response equations were computed. Models were evaluated for adequacy by inspection of the residuals and by lack of fit tests. Homogeneity of response to O_3 over levels of other factors or over studies was tested with likelihood ratio tests (Gallant, 1987) comparing residual sum of squares when a common response is assumed to the residual sum of squares obtained when each

subset is allowed to have its own response to O_3. The first category of response equations included a dose-response equation for each study or for subsets of each study when the responses within the study were shown to be heterogeneous. The second category of dose-response equations contained common response equations computed over subsets of experiments as allowed by tests of homogeneity over studies. The grouping of experiments into homogeneous subsets is dependent on the sequence in which the responses are compared. Consequently, other groupings may be as reasonable as those presented. Finally, in spite of heterogeneity, all data for each species were combined to develop an average response curve for the species, the Category III models.

RESULTS AND DISCUSSION

The results of the residuals analyses indicated that the dose-response models should be fitted using the original scale and ordinary least squares for barley (*Hordeum vulgare* L.), forage, lettuce (*Lactuca sativa* L.), peanut (*Arachis hypogaea* L.), sorghum [(*Sorghum bicolor* (L.) Moench], tobacco (*Nicotiana tabacum* L.), and tomato (*Lycopersicon esculentum* Mill.); using the original scale and weighted least squares for alfalfa, cotton, kidney bean (*Phaseolus vulgaris*), turnip (*Brassica rapa* L.), and wheat; and using weighted least squares on the square root transformed scale for corn and soybean. The weights used in all cases were the reciprocals of the estimated error variances from the analyses of variance on the appropriate scales.

Separate Weibull response equations for O_3 were fitted by levels of any other factors (cultivars, moisture, or SO_2) that caused significant heterogeneity of response to O_3. In total, 54 Category I Weibull response equations (not presented) were used to characterize the responses to O_3 in the 43 studies. There was significant heterogeneity of response to O_3 among cultivars of corn in the Argonne 1985 study, of soybean in the Argonne 1983 study, and of wheat in the Argonne 1982 study. Moisture stress caused significant heterogeneity of response for cotton in the Shafter 1981 and the Raleigh 1985 studies, and for soybean in the Argonne 1986, Beltsville 1982, and Beltsville 1983 studies. In six of the 12 studies in which SO_2 was used as a treatment factor, there was a significant effect of SO_2 on yield. In only one case, Raleigh 1982 cotton, was there a suggestion of heterogeneity of response to O_3 for different levels of SO_2. In this case, the $SO_2 \times O_3$ interaction was significant ($\alpha = 0.01$) for the polynomial model but was not significant for the Weibull model. The $SO_2 \times O_3$ interaction for the polynomial model was reported as nonsignificant (*P*-value was 0.09) by Heagle et al. (1986a, 1988) due to several differences between the analyses. The analyses reported by Heagle included ambient air plots in the analysis and used 7-h treatment mean levels of O_3.

In a few cases for the Category I models (Argonne 1983 soybean cv. Pella and Williams, Beltsville 1982 soybean under moisture stress, Raleigh 1983 soybean, and Ithaca 1982 wheat), the least squares solution was restricted by setting the shape parameter (λ) in the Weibull model equal to one and estimating only the scale parameter (ω). This restriction was prompted by an exceptionally large observed decline in yield between the charcoal-filtered treatment and the nonfiltered treatment, which caused the unrestricted least squares estimate of λ to be much less than 1.0 and the estimates of α, the theoretical yield at zero dose, to be extraordinarily large and meaningless. Restricting the solution in these cases caused only slight increases in the residual sum of squares but gave more realistic estimates of the parameters.

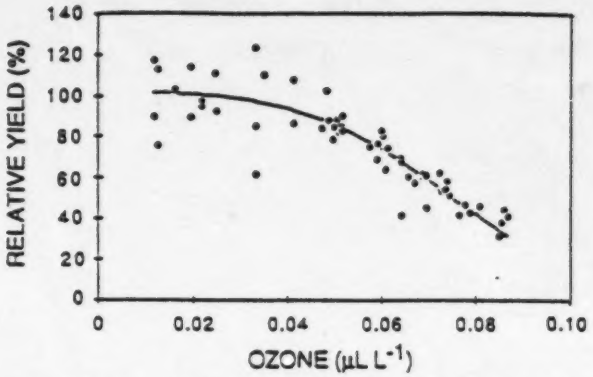

Fig. 1. Category II Weibull response equation for cotton (C82, R82, and R85 M = 1) scaled to show yield relative to yield at O_3 = 0.025 μL L^{-1}. The metric used is the 12-h O_3 mean. Data points have been adjusted to remove all fixed effects except the effects of O_3.

The Category II Weibull dose-response equations combined information from different studies within the same crop for which the responses to O_3 could be considered homogeneous. In all cases, subsets of data within studies that showed significant heterogeneity of response, as described for the Category I models, were kept separate for subsequent testing of homogeneity of response for the Category II models. The Category II equations are summarized in Table 1. The combined models allowed each study and/or cultivar (identified by the α-label) to have its own estimate of α, $\hat{\alpha}$, to provide for differences in yield levels. No Weibull response equations are given for alfalfa, Argonne 1984; barley, 1982 and 1983; and cotton, Shafter 1985 because the effects of O_3 were not significant in these studies, which in turn caused convergence problems in the nonlinear estimation. Standard errors of the parameter estimates, computed from the first-order approximations of the variances, are shown in parentheses.

For illustration, plots of the fitted Category II response equations are shown for cotton (Fig. 1) and soybean (Fig. 2). The regression line in each figure expresses yield relative to yield at O_3 = 0.025 μL L^{-1} and for plotting purposes the data points have been adjusted to remove all effects except the relative O_3 effects and random error; that is, site, year, cultivar, linear SO_2, and linear moisture effects have been removed.

The Category III response equations are summarized in Table 2. The Category III response curve for each species is the best-fitting common Weibull response curve where the model has included α-terms to account for all site, year, block, cultivar, linear SO_2, and linear moisture effects. In all crops tested in more than one environment except tomato, the Category III Weibull equations involved combining over nonhom-

Table 1. Parameter estimates for the Category II (homogeneous) Weibull equations. Estimated approximate standard errors are shown in parentheses.†

Studies in model‡ a label:	$\hat{a}$	$\alpha(x)$ lab el:§	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
			Alfalfa		
1. C84 and C85					
C84:	25480	M84:	4108 (835)	0.179 (0.023)	1.78 (0.40)
C85:	20821	M85:	8884 (823)		
2. A84—no significant response. Weibull model not fit					
			Barley		
C82 and C83—no significant response. Weibull model not fit					
			Corn¶		
1. A81 (cv. Pioneer 3780 and PAG-397)					
Pioneer 3780:	10750			0.108 (0.001)	4.34 (0.49)
PAG-397:	12755				
2. A85 (cv. Pioneer 3780 and LH74 × FR35)					
Pioneer 3780:	11036	S:	1581 (3839)	0.139 (0.004)	3.27 (0.54)
LH74 × FR35:	11791				
3. A85 (cv FR20A × FR35 and FR20A × FR634)					
FR20A × FR35:	12426	S:	−2902 (4912)	0.121 (0.003)	2.92 (0.35)
FR20A× FR634:	14736				
			Cotton		
1. C81 (M = 1)	14090			0.112 (0.003)	3.00 (0.48)
2. C81 (M = 0)	8819			0.128 (0.020)	4.40 (3.17)
3. C82, R82, and R85 (M = 1)					
C82:	5073	S:	289 (388)	0.083 (0.002)	3.53 (0.39)
R82:	2987	T:	31 (125)		
R85, M = 1:	3596	M:	388 (422)		
4. R85 (M = 0)	3360			0.112 (0.053)	4.07 (4.30)
5. C85—no significant response, Weibull model not fit.					
			Forage		
1. I84 and I85					
I84:	4069	S:	−9952 (9514)	0.085 (0.011)	3.10 (1.46)
I85:	2037	Cov:	4486 (1021)		
2. R84 and R85					
R84:	10364	M:	1196 (250)	0.133 (0.015)	2.37 (0.74)
R85:	7440				
			Kidney Bean		
1. I80	2809			0.230 (0.032)	2.71 (0.39)
2. I82	2475			0.114 (0.005)	2.66 (0.61)
			Lettuce		
C83	60257			0.120 (0.004)	9.76 (3.45)
			Peanut		
R80	7428			0.109 (0.002)	2.27 (0.22)
			Sorghum		
A82	8157			0.314 (0.162)	2.07 (1.22)

Table 1. continued

ogeneous responses. Consequently, each should be regarded as an approximation of the average response of the crop. It should be noted that the estimates of ω and λ for the Category III curves are not simple averages of the individual estimates of ω and λ.

The parameter estimates in Tables 1 and 2 reveal the impact of treatment effects for each species. Covariates were significant and remained in the model for five studies (% virus infected plants for Argonne 1980 soybean, and Argonne 1982 and 1983 wheat; total fresh fruit weight in companion plots for 1981 tomato; and relative plant density for Ithaca 1984 forage). A covariate for the tobacco study, a measure of total leaf area before exposures were started, was nearly significant ($\alpha = 0.05$) in the analysis of variance but clearly nonsignificant when the dose-response model was fit. The Weibull parameter estimates with the covariate present are given in Heagle et al., 1987. The effect of moisture stress was significant ($\alpha = 0.05$) in 14 of 16 experiments, but only five showed a significant effect of moisture on the O_3 response curve ($\alpha = 0.05$); Argonne 1986, Beltsville 1982 and Beltsville 1983 soybean, Riverside 1981 cotton, and Raleigh 1985 cotton. Sulfur dioxide caused a significant linear decline in yield for soybean, Eq. [1], [2], and [3], and tomato (Table 1).

The detrimental effect of O_3 was significant in all crops tested except barley, but the crops different ap-

Table 1. continued

Soybean†					
1. A80, A83SO2 (cv. Amsoy and Corsoy), A83cv (cv. Corsoy and Pella), R82, R84, and R86					
A80:	1793	S:	−1073 (240)	0.101 (0.004)	2.21 (0.32)
A83SO2, Amsoy:	1245	M:	882 (169)		
A83SO2, Corsoy:	938	Cov:	−144 (112)		
A83cv, Corsoy:	1141				
A83cv, Pella:	1836				
R82:	3839				
R84:	3190				
R86:	6931				
2. A83cv (cv. Amsoy and Williams), A85, B82 (cv. Forrest and Williams, M = 0), B83 (cv. Williams and Corsoy, M = 0), and R83					
A83cv, Amsoy:	1122	M(A85):	1156 (381)	0.130 (0.010)	0.99 (0.29)
A83cv, Williams:	1560	M(R83):	2917 (349)		
A85:	3688	S:	−11636 (4130)		
B82, Forrest, M = 0:	5481				
B82, Williams, M = 0:	4998				
B83, Williams, M = 0:	7647				
B83, Corsoy, M = 0:	6261				
R83:	2867				
3. B81 (cv. Essex and Williams), B82 (cv. Forrest and Williams, M = 1), B83 (cv. Williams and Corsoy, M = 1), I81, and R81					
B81, Essex:	4606	S(B82, B83):	−6251 (852)	0.092 (0.002)	1.72 (0.16)
B81, Williams:	4959	S(R81):	−4149 (491)		
B82, Forrest, M = 1:	5279				
B82 Williams M = 1:	5574				
B83, Williams, M = 1:	8163				
B83 Corsoy M = 1:	6049				
I81:	2775				
R81:	4604				
4. A86 (M = 1)	5291			0.118 (0.013)	3.61 (1.58)
5. A86 (M = 0)	3804			0.097 (0.005)	70.66 (156)
Tobacco					
R83	6438			0.145 (0.009)	1.66 (0.40)
Tomato					
C81 and C82					
C81:	67417	S:	−36559 (13293)	0.204 (0.068)	1.67 (0.75)
C82:	59585	Cov:	0.61 (0.16)		
Turnip					
R80 (cv. Just Right, Tokyo Cross, Purple Top, and Shogoin)					
Just Right:	1209			0.093 (0.002)	2.70 (0.37)
Tokyo Cross:	1795				
Purple Top:	691				
Shogoin:	505				
Wheat					
1. A82 (cv. Roland)	5446	Cov:	36.7 (5.1)	0.113 (0.005)	1.70 (0.30)
2. A82 (cv. Abe and Arthur)					
Abe:	5334	Cov:	38.0 (3.9)	0.143 (0.005)	2.52 (0.40)
Arthur:	4578	Cov:	24.9 (3.1)		
3. A83 (cv. Abe and Arthur)					
Abe:	6096	Cov:	26.0 (4.6)	0.116 (0.010)	7.95 (3.16)
Arthur:	5214	Cov:	7.5 (4.6)		
4. I82	8550			0.050 (0.004)	1.00 (0.00)
5. I83	4737	S:	−62 (1227)	0.115 (0.010)	1.94 (0.85)

† The O_3 metric was the 7-h seasonal mean for barley, kidney bean, lettuce, peanut, sorghum, tomato, turnip, and wheat; and the 12-h seasonal mean for alfalfa, corn, cotton, forage, soybean, and tobacco.

‡ Study code is the site (A = Argonne, B = Beltsville, C = California, I = Ithaca, and R = Raleigh) followed by the last two digits of the year.

§ S designates the coefficient for seasonal SO_2 metric, which was the 4-h seasonal mean ($\mu L\ L^{-1}$) for all studies except Alfalfa A84, where it was the sum of hourly exposures during the exposure period; Forage I84 and I85, where it was the 24-h average for exposure days; and Tomato C81 and C82, where it was the 7-h average. M = 0 if water stressed, M = 1 if well-watered; T = 1 if a frustum top is present, T = 0 otherwise; and Cov = covariate (centered to mean zero).

¶ Analysis was conducted on square root transformed data but parameter estimates are on original yield scale.

preciably in their sensitivity to O_3 with soybean being the most sensitive. The estimated relative yield losses for a change in O_3 from 0.025 to 0.05 $\mu L\ L^{-1}$ (based on the Category III equations) varied from less than 1% (barley and lettuce) to as much as 20% (soybean). Likewise, the nature of the response varied from a nearly linear response for kidney bean, soybean, tobacco, and tomato (λ = 1.35–1.67), to a slightly delayed response for alfalfa, cotton, forage, peanut, and sorghum (λ = 1.95–2.27), to the more marked delay in response of corn, lettuce, turnip, and wheat (λ = 2.56–9.76), Tables 1 and 2.

Table 2. Parameter estimates for the Weibull average response to O_3 for each species: Category III (heterogeneous) models. The species response equations for lettuce, peanut, sorghum, tobacco, tomato, and turnip are given in Table 1. Estimated approximate standard errors are shown in parentheses.†

α label:	$\hat{\alpha}$	$\alpha(x)$ label:	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
			Alfalfa		
A84:	1509	S:	7.5 (6.7)	0.178 (0.028)	2.07 (0.55)
C84:	24758	M, C84:	3987 (952)		
C85:	20297	M, C85:	8646 (933)		
			Corn‡		
A81, Pioneer 3780:	10647	S:	−251 (3690)	0.124 (0.002)	2.83 (0.23)
A81, PAG-397:	12640				
A85, Pioneer 3780:	12246				
A85, LH74 × FR23:	13069				
A85, FR20A × FR634:	14437				
A85, FR202 × FR35:	12140				
			Cotton		
C81:	10924	M, C81:	4335 (692)	0.111 (0.005)	2.06 (0.33)
C82:	4835	M, C82:	347 (587)		
C85:	7050	M, C85:	6115 (2599)		
R82:	3221	M, R85:	116 (386)		
R85:	3849	S:	314 (541)		
		T:	58 (173)		
			Forage		
I84:	2619	S:	−9818 (10114)	0.139 (0.015)	1.95 (0.56)
I85:	742	Cov:	4299 (1029)		
R84:	10726	M:	1232 (247)		
R85:	7712				
			Kidney Bean		
I80:	3093			0.279 (0.079)	1.35 (0.70)
I82:	2178				
			Soybean‡		
A80:	1933	M:	920 (103)	0.107 (0.003)	1.58 (0.16)
A83SO2, Amsoy:	1593	S:	−1964 (256)		
A83SO2, Corsoy:	1272	Cov:	−186 (134)		
A83cv, Corsoy:	1238				
A83cv, Pella:	1979				
A83cv, Amsoy:	1201				
A83cv, Williams:	1604				
A85:	3519				
A86:	5435				
B81, Essex:	3322				
B81, Williams:	3667				
B82, Forrest:	4436				
B82, Williams:	4327				
B83, Williams:	7017				
B83, Corsoy:	5380				
I81:	1763				
R81:	3141				
R82:	4141				
R83:	3466				
R84:	3440				
R86:	7338				
			Wheat		
A82, Abe:	5426	Cov82, Abe:	40.1 (7.3)	0.136 (0.006)	2.56 (0.41)
A82, Arthur:	4647	Cov82, Arthur:	25.4 (6.1)		
A82, Roland:	4553	Cov82, Roland:	28.8 (8.2)		
A83, Abe:	6871	Cov83, Abe:	15.6 (8.7)		
A83, Arthur:	5878	Cov83, Arthur:	2.8 (8.8)		
I82:	3643	S:	−57 (1502)		
I83:	4055				

† See footnote to Table 1 for definition of O_3 and SO_2 dose metrics. M = 0 if water stressed, M = 1 if well-watered; T = 1 if frustum top is present, T = 0 otherwise; and Cov = covariate (centered to mean zero).

‡ Analysis was conducted on square root transformed data but parameter estimates are on original yield scale.

In a few cases, the yield response to O_3 was not sufficient to provide adequate definition of the Weibull response curve and convergence to a solution in the nonlinear estimation was not obtained (Table 1). The model in such cases is more complex than is warranted by the response shown in the data, and if convergence is obtained, the parameters are not well defined and the variances of their estimates tend to be large (Rawlings, 1988, p. 400). The latter is illustrated by large standard errors for $\hat{\lambda}$ in cotton Eq. [2] and [3], lettuce, soybean Eq. [5], and wheat Eq. [3], and for both $\hat{\omega}$ and $\hat{\lambda}$ in sorghum. These large standard errors arose primarily because the chosen levels of O_3 for the studies were not sufficiently high to provide an adequate definition of the Weibull response (Dassel and Rawlings, 1988), but also because the first-order

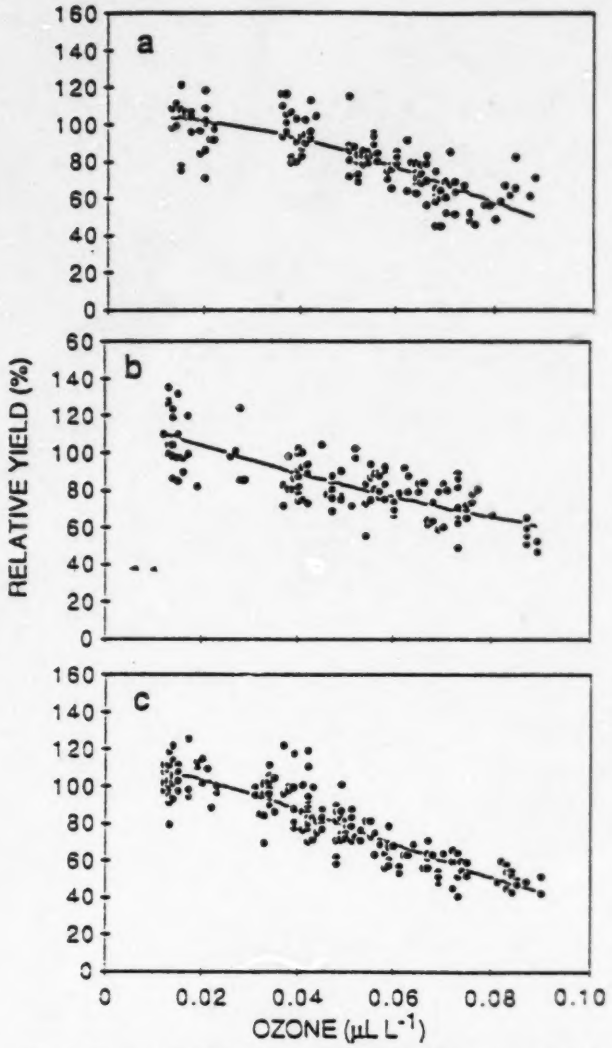

Fig. 2. Category II Weibull response equations for soybean scaled to show yield relative to yield at O_3 = 0.025 μL L^{-1}. The metric used is the 12-h O_3 mean. Data points have been adjusted to remove all fixed effects except the effects of O_3. (a) Soybean Eq. [1], combined response for A80, A83SO2 (cv. Amsoy and Corsoy), A83cv (cv. Corsoy and Pella), R82, R84, and R86. (b) Soybean Eq. [2], combined response for A83cv (cv. Amsoy and Williams), A85, B82 (cv. Forrest and Williams, M = 0), B83 (cv. Williams and Corsoy, M = 0), and R83. (c) Soybean Eq. [3], combined response for B81 (cv. Essex and Williams), B82 (cv. Forrest and Williams, M = 1), B83 (cv. Williams and Corsoy, M = 1), I81, and R81.

approximation of the variances in these cases is likely to be inadequate and overestimate the true variance (Dassel, 1988, personal communication).

It should be recognized that the average O_3 response curve (Category III) for each crop for a variety of reasons is not a valid characterization of the average effect of O_3 pollution on agricultural production for the crop. The environments sampled for even the most studied species, soybean, cannot be considered an adequate sample of environments for soybean production, each crop was represented by only one or a few

Table 3. Wald confidence interval estimates (P = 0.05) of percentage yield loss from ozone relative to yield at O_3 = 0.025 μL L^{-1} based on the Category II Weibull response equations.†

Model‡	Ozone (μL L^{-1}) 0.04	0.05	0.06
	%		
Alfalfa	(1.9, 5.8)	(4.3, 9.8)	(7.4, 13.9)
Corn			
1	(0.1, 2.2)	(1.0, 5.6)	(3.5, 11.1)
2	(1.0, 4.8)	(2.9, 9.8)	(6.3, 16.1)
3	(−0.1, 2.7)	(0.3, 5.3)	(1.6, 10.0)
Cotton			
1	(0.6, 6.2)	(2.6, 12.2)	(6.9, 19.5)
2	(−2.9, 3.9)	(−6.2, 9.2)	(−10.0, 16.9)
3	(3.5, 8.4)	(10.2, 17.3)	(21.8, 30.1)
4	(−6.9, 9.5)	(−11.5, 18.4)	(−11.3, 26.1)
Forage			
1	(−0.9, 15.2)	(5.4, 26.0)	(17.6, 36.8)
2	(0.2, 7.4)	(2.3, 13.0)	(6.3, 18.6)
Kidney Bean			
1	(−0.8, 2.1)	(−1.3, 4.0)	(−1.6, 6.4)
2	(−0.2, 8.7)	(1.5, 16.2)	(5.5, 24.3)
Lettuce	(0.0, 0.0)	(−0.1, 0.1)	(−0.5, 0.7)
Peanut	(4.0, 8.9)	(8.7, 16.3)	(15.2, 24.4)
Sorghum-Soybean	(−1.3, 3.0)	(−1.7, 5.1)	(−1.9, 7.3)
1	(5.5, 10.5)	(12.0, 18.6)	(20.4, 27.2)
2	(8.8, 13.2)	(15.0, 20.2)	(20.7, 26.7)
3	(10.6, 14.0)	(19.4, 23.6)	(28.7, 33.2)
4	(−2.4, 5.7)	(−3.6, 11.8)	(−2.9, 19.0)
5	(0.0, 0.0)	(0.0, 0.0)	(0.0, 0.0)
Tobacco	(1.3, 11.1)	(4.2, 18.0)	(8.4, 24.3)
Tomato	(0.4, 6.6)	(2.0, 10.6)	(4.5, 14.4)
Turnip	(3.9, 10.5)	(9.9, 19.8)	(18.9, 30.1)
Wheat			
1	(4.9, 13.2)	(10.2, 21.3)	(16.9, 29.8)
2	(0.7, 4.8)	(2.3, 9.2)	(4.9, 14.1)
3	(−0.1, 0.1)	(−0.4, 0.6)	(−1.1, 2.1)
4	(19.7, 32.2)	(32.8, 45.9)	(44.4, 56.4)
5	(−1.2, 16.1)	(1.6, 25.3)	(7.1, 34.3)

† No Weibull model was fit to barley. For both corn and soybean, the analysis was based on the square root scale but percentage losses are expressed on the original scale.

‡ Model numbers correspond to the models in Table 1, the Category II equations. Missing model numbers correspond to cases in which the response to O_3 was not significant and the Weibull response model was not fit.

cultivars, and the averaging of the responses did not take into account relative economic importance of cultivars or geographical regions to the total agricultural production of the crop. Nevertheless, the Category III dose-response equations provide a useful rough summary of the average responses to O_3 in the NCLAN studies. Impressions of the variability in yield response to O_3 can be gained from inspection of the range of responses in the homogeneous subsets, Category II responses.

The Wald 95% confidence interval estimates of predicted relative yield losses, based on the Category II models, are given in Table 3. All relative yield losses are computed as the estimated percent decrease in yield corresponding to a change in O_3 from 0.025 μL L^{-1} to the level indicated in the column headings. The intervals presented, O_3 = 0.04, 0.05, and 0.06 μL L^{-1}, represent the estimated penalty being paid for current levels of O_3 pollution, or the benefits that might be realized with more restrictive standards on O_3. Technically, the model does not allow negative losses so that the negative lower bounds shown in some confidence intervals are a direct reflection of the Wald approximation. The anomalous zero lower and upper bounds for soybean (Eq. [5]) are a direct reflection of

the extremely large estimate of λ, which causes both the estimated yield loss and the approximated variance of the loss to be zero.

The Wald confidence interval estimates of relative yield losses (Table 3) assume normality of the estimates and use the first-order approximations of the variances provided by the nonlinear regression program. It is known that the Wald confidence limits can be inadequate in some cases (Gallant, 1987). Second-order approximations of the variances and simulations for special cases suggest that the first-order approximations of the variances for the Weibull model tend to overestimate the true variances when there is a breakdown in the first-order approximation (Dassel, 1987) and, thus, the Wald confidence interval estimates of RYL probably error on the side of being conservative (too large). Comparisons of Wald confidence limits with more exact confidence interval estimates using the likelihood ratio statistic (Gallant, 1987) and the Clarke adjustment (Clarke, 1987) for several of the NCLAN equations showed that the Wald approximations were clearly inadequate in some individual studies where the Weibull response was not well defined and/or where the experimental variance was high. In other individual studies, such as peanut, and in all cases investigated that used combined data, the Wald approximation gave excellent agreement with the more exact methods (Somerville et al., 1988, personal communication).

The heterogeneity of observed responses among studies could be due to genetic differences in the cultivars used or to any of many soil, climatological, and management differences. In these analyses, the pooled effect of all such differences was treated as a fixed effect assigned to each study. The standard errors of the estimates were computed using this fixed effects model. While the sampling of environments for such studies can never be truly random, more reasonable estimates of precision would be obtained by regarding these effects as random. Work is in progress to modify programs to handle random effects in nonlinear models.

CONCLUSIONS

The NCLAN research has demonstrated significant detrimental causal effects of O_3 pollution on 13 of 14 crop species studied, and has quantified the relationship in dose-response equations and estimated percentage yield losses from current levels of O_3 pollution. Yield losses ranged from near zero to as much as 20%. The response to O_3 was influenced by crop, cultivar, and moisture stress, but only one study gave evidence that presence of SO_2 pollution might affect the nature of the O_3 response curve. Heterogeneity of response among studies suggests that there are other environmental factors yet to be identified that alter the impact of O_3. More research is needed to identify other important interacting factors, to study the mechanisms of O_3 pollution damage, and to more adequately characterize the dose-response relationships.

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